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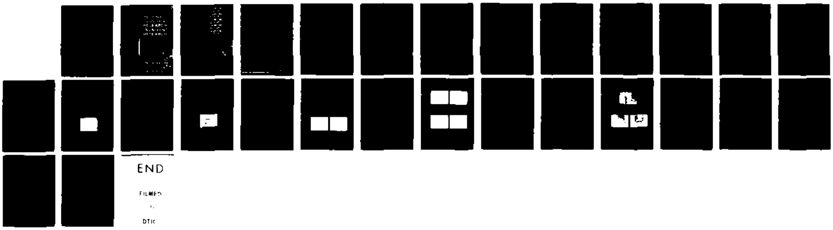

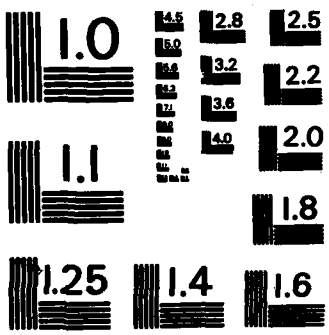
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Final
Research Report

The Response of Solar Cells to Microwave Radiation

Glenn E. Fanslow
August 1982

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The Response of Solar Cells to Microwave Radiation

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Submitted to
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A transmission line analogy is used to show that microwaves would induce little if any voltage in solar cells or solar cell systems. Experimental verification of this result is obtained by irradiating solar cells with microwave energy at 2.45 GHz. Preliminary results describing the heating of solar cells by microwaves as well as unusual voltages produced in a series combination of solar cells are presented.

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THE RESPONSE OF SOLAR CELLS TO MICROWAVE RADIATION

by

Glenn E. Fanslow

ABSTRACT

A transmission line analogy is used to show that microwaves would induce little if any voltage in solar cells or solar cell systems. Experimental verification of this result is obtained by irradiating solar cells with microwave energy at 2.45 GHz. Preliminary results describing the heating of solar cells by microwaves as well as unusual voltages produced in a series combination of solar cells are presented.

INTRODUCTION

The investigation of the response of solar cells to microwaves was initiated by assuming that a solar cell may be represented as an infinite glass-semiconductor-conductor slab in free space. It also assumed that the microwave radiation would be a linearly polarized plane wave that was normally incident upon the slab at the free space-glass interface. The system is shown in Figure 1. (The dimensions and materials are taken from "High Efficiency Solar Panel [HESP], Spectrolab Final Report AFAPL-TR-77-36, July 1977, and information supplied by Mr. J. Fodor of Spectrolab.) Not appearing in this model are the top contact metalization, the junction diode in the silicon, and the insulating substrate that supports the solar cell.

The voltages and currents that would be produced in a solar cell by microwave radiation were determined by using the transmission line analog of the solar cell shown in Figure 2. The impedance for each section of the line is determined from the general expression

$$\eta = \sqrt{\frac{\mu}{\varepsilon + \frac{\sigma}{j\omega}}} = \sqrt{\frac{\mu}{\varepsilon}\ \frac{1}{1 + j\ \frac{\sigma}{j\omega\varepsilon}}} \tag{1}$$

where $\mu = 4\pi 10^{-7}$, $\varepsilon = (8.854)(10^{-12})\varepsilon_r$, ε_r is the relative dielectric constant of the material, σ is the conductivity of the material, and $\omega = 2\pi f$ where f is the frequency of the microwave signal in Hertz. For dielectric materials, such as glass, $\sigma/j\omega\varepsilon << 1$ and

$$\eta \cong \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r}} = \frac{377}{\sqrt{\varepsilon_r}} \tag{2}$$

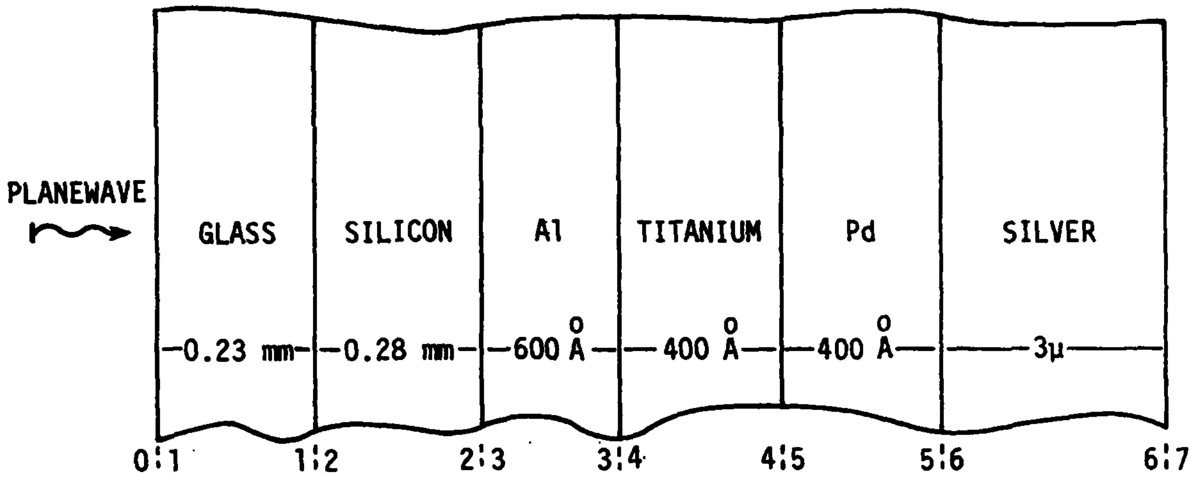


Fig. 1. Modeling of the solar cell as infinite slabs of glass, silicon and conductor. The glass is a cover glass, the silicon is the solar cell, and 3-6 is the back contact.

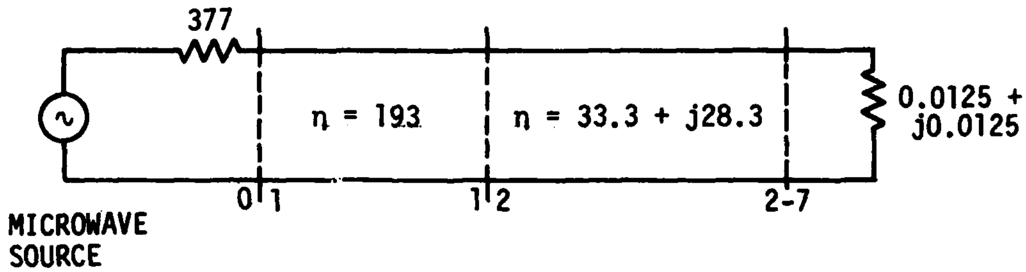


Fig. 2. T-line analog of the solar cell subjected to microwave radiation--impedances for f = 2.45 GHz.

For good conductors, such as silver, $\sigma/j\omega\varepsilon >> 1$ and

$$\eta \cong \sqrt{\frac{\mu}{(\sigma/j\omega)}} = \sqrt{j\,\frac{\omega\mu}{\sigma}} \tag{3}$$

For poor conductors, such as 10 ohm-cm silicon, Equation 1 is used.

The voltage produced by the microwave radiation will be across the cell and the result may be modeled as shown in Figure 3. The inherent capacitance of the diode acts as a short circuit for the microwave signal and the only voltage appearing across the solar cell will be the rectified envelope of the modulation signal. This is illustrated in Figure 4.

VOLTAGE CALCULATIONS

The voltage "applied" to the solar cell may be determined by solving for the electric fields at the front and back contacts of the solar cell. In the transmission line analog, the electric field at each boundary will depend on the reflection coefficient at the boundary. The reflection coefficient is given by the expression

$$\Gamma = \frac{\eta_L - \eta_0}{\eta_L + \eta_0} \tag{4}$$

where η_L is the load impedance and η_0 is the characteristic impedance of the line leading to the load. For example, the input impedance at the free space-glass boundary will be approximately

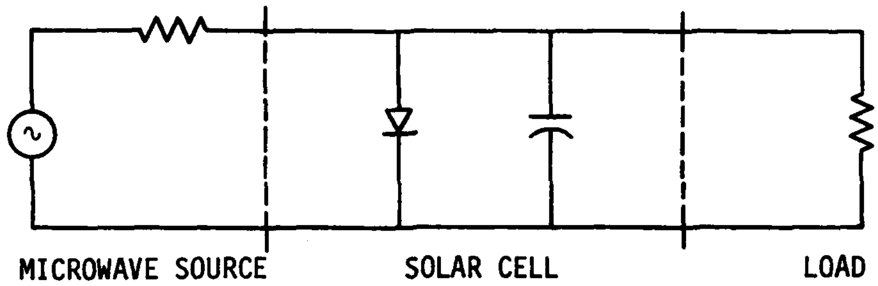


Fig. 3. Circuit model of the solar cell subjected to microwave radiation.

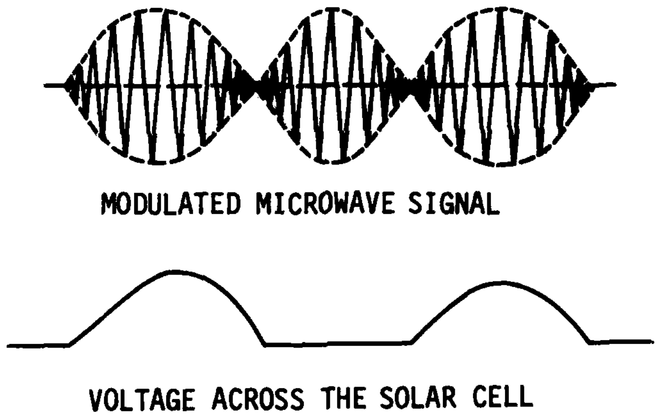


Fig. 4. Modulated microwave signal and detected signal.

$$\eta_{01} = 193\,\frac{\eta_{12}+j193\tanh\gamma d_1}{193+j\eta_{12}\tanh\gamma d_1} \tag{5}$$

The value η_{12} is the input impedance at the glass-semiconductor boundary and it, in turn, will depend on η_{23}, the input impedance at the semiconductor-aluminum interface. This impedance calculation must be repeated through the transmission line starting from the silver-air interface. When this is performed at 2.45 GHz, the input impedance at the air-glass interface will be approximately $j7.66 = 7.66\underline{/90°}\ \Omega$, and the reflection coefficient there will be approximately $1\underline{/177.67°} = -0.999+j0.0406$. (See Appendix I.) This indicates that practically all of a 2.45 GHz signal will be reflected from the solar cell. The result would be that only a small fraction of the incident energy will be transmitted through the cell to the back contact, and the voltage produced across the cell will be very low. This may be illustrated by determining the relative signal levels at the front and back contacts.

Although most of the incident signal will be reflected at the air-glass interface, the portion of this signal that will be transmitted through the glass will be

$$\tau = \frac{2\eta_{01}}{\eta_{01}+377} = \frac{2(j7.66)}{j7.66+377} \cong 0.041\underline{/88.8°} \tag{6}$$

The signal passing through the glass will be reflected at the glass-semiconductor interface, and the transmission coefficient there will be

$$\tau = \frac{2(j5.39)}{j5.39+193} \cong 0.0559\underline{/88.4^\circ} \quad (7)$$

Thus, the signal at the glass-semiconductor interface will be lower than that of the incoming signal by a factor of 0.0023. Finally, on the assumption that the impedance at the back contact is zero, it may be said that the voltage across the solar cell is equal to that present at the front contact. (This would be nearly true since the magnitude of the impedance at the back contact is approximately 0.0177 Ω.) Thus, for an incoming microwave signal, having a peak voltage of one volt and 100% modulation, the peak value of the voltage seen across the solar cell would be approximately 2 millivolts.

EXPERIMENTAL

Preliminary testing of the voltage produced by a solar cell subjected to microwaves was performed using the circuit shown in Figure 5. The intent of this experiment was to validate the model of the solar cell being subjected to microwave radiation. (The voltage across the solar cell will not be the same as that read on the meter of the microwave generator.) The result of this testing, when an indicated voltage of 0.6 volts was applied to one solar cell, is shown in Figure 6. The voltage measured by the oscilloscope was approximately 0.03 volts. If a direct application of the preceding analysis were valid, this would correspond to an incident r-f voltage having a peak of 15 volts being applied to the cell.

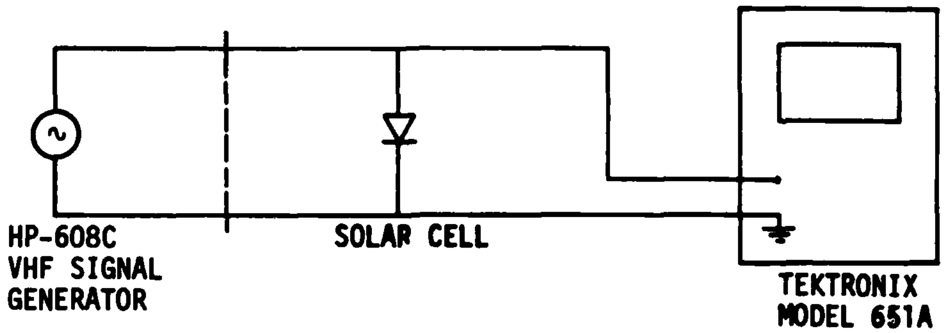


Fig. 5. Application of a modulated microwave signal to a solar cell.

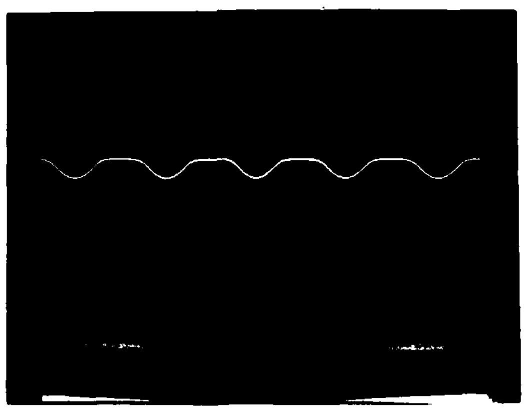


Fig. 6. Voltage across the solar cell when tested as in Figure 5. Microwave signal 215 MHz, 100% modulation voltage as read by the meter on the microwave generator 0.6V. Oscilloscope settings vertical 0.05 V/div; horizontal 0.5 msec/div.

Additional testing of a single cell was performed by placing the cell inside of a section of WR-340 waveguide. The method is illustrated in Figure 7.

The solar cell was perpendicular to the walls of the waveguide. It was inserted through a slot in the waveguide and positioned near the end of the slot so that fields seen by the solar cell would not be distorted by the presence of the slot. The type of signal viewed on the oscilloscope is shown in Figure 8. Transmitted power for this case was 50 watts. Since the power meters indicate the average power being transmitted, it is estimated that the actual peak value of r-f power will be larger by a factor of approximately 2.8. The incident electric field intensity would have a peak value of approximately 15,000 volts per meter.

The inside of a waveguide proved to be a rather hostile environment for testing. There were instances of arcing from the solar cell to the leads, from the leads to the waveguide, and the like. Additional effects produced were heating of the solar cell and shorting out of the cell. With the solar cell inside the waveguide, it was not possible to obtain temperature measurements. Also, because of problems with arcing, and because there were only a limited number of cells available, it was only possible to obtain an estimate of the fields present when the cells shorted out. This occurred when the transmitted power was 150 to 200 watts. The approximate value for the incident field at this power level is 30,000 volts per meter.

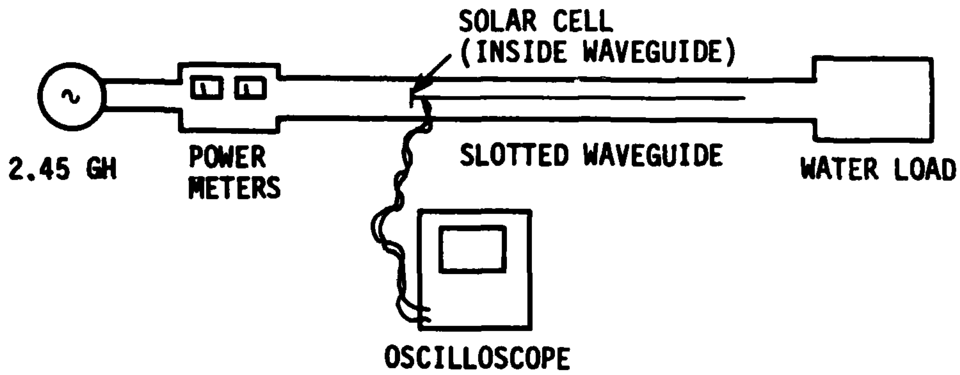


Fig. 7. Testing of a solar cell inside a waveguide.

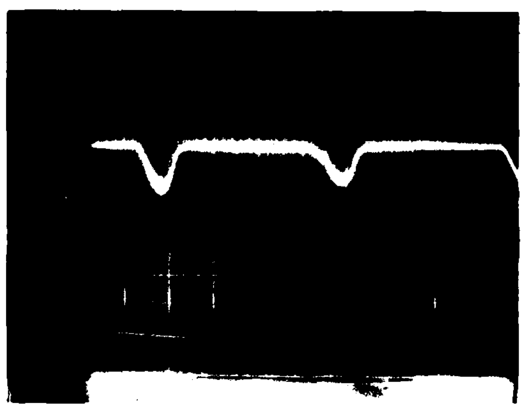


Fig. 8. Voltage across the solar cell when tested as shown in Figure 7. Vertical 0.02 V/div; horizontal 2 msec/div.

TESTING IN ANECHOIC CHAMBER

Testing in an anechoic chamber was performed using the set-up shown in Figure 9.

The solar cell was supported by a glass rod that rested on blocks of ECCOSORB. Leads from the solar cell to the oscilloscope were sheltered from the incoming microwave energy by the solar cell and ECCOSORB. Examples of the voltages produced across the cells are shown in Figures 10 through 12. In all cases the average power transmitted through the waveguide was one kilowatt. The distance from the front of the horn antenna to the solar cells was 10 centimeters. Notice that in part a of each of the figures, the front contact fingers were parallel to the E-field and in part b the front contact fingers were perpendicular to the E-field. In Figure 10 there was one cell, in Figure 11 there were 4 cells in series, and in Figure 12 there were 4 cells in parallel.

The results in Figure 10 show the effect of the presence of the top contact fingers. In part a, where the fingers were parallel to the E-field, the coupling of the field to the fingers was maximum. Energy coupled to the fingers was not free to be transmitted through the silicon to the bottom contact, and the voltage developed across the cell was reduced. This may be contrasted with the voltage developed across the cell in part b. In this case, with the fingers perpendicular to the E-field, the coupling of the field to the fingers was minimal and the induced voltage was higher. From these measurements it would appear as though when the E-field is parallel to the top contact finger, the induced voltage will be approximately 15 to 20% smaller than when

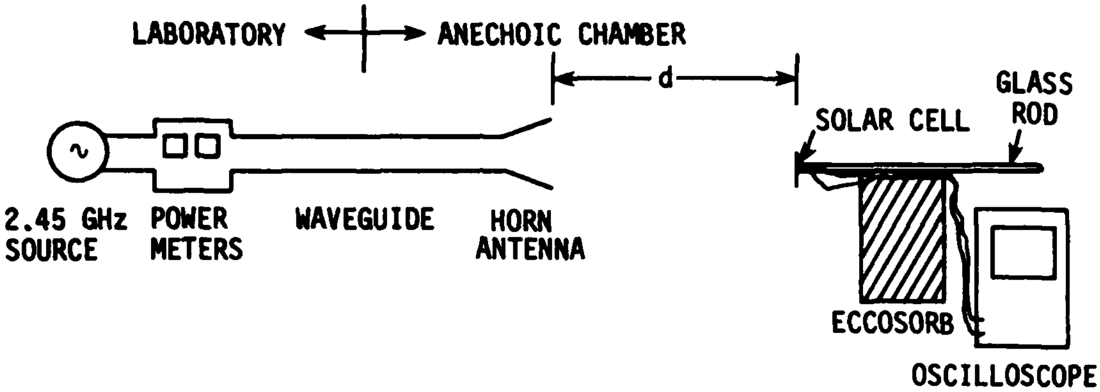


Fig. 9. Testing of solar cells in an anechoic chamber.

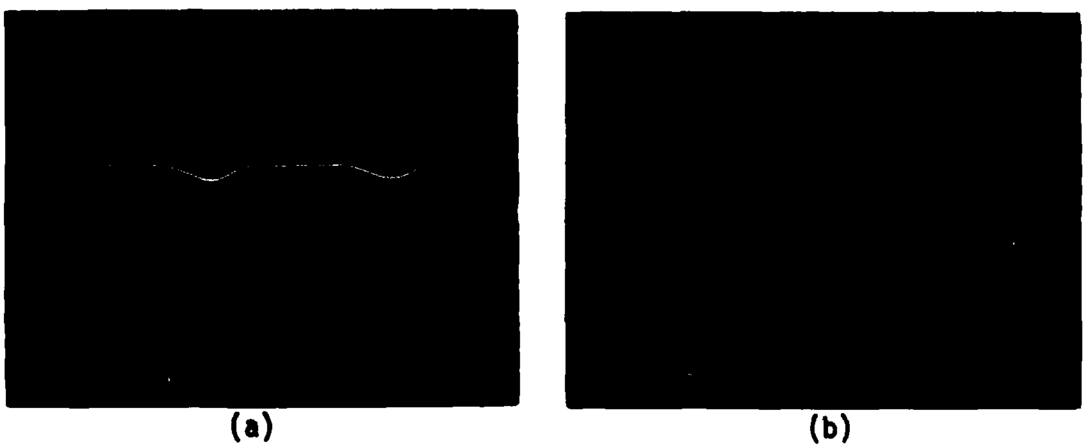


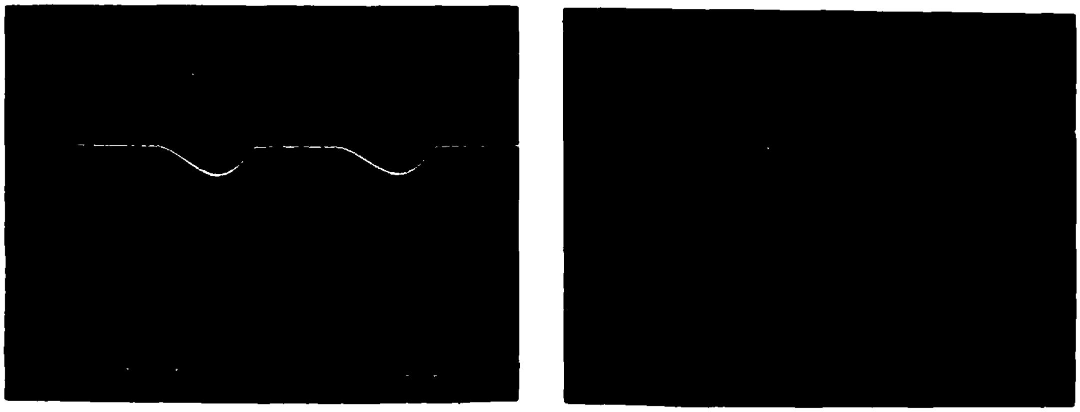
Fig. 10. Voltage across a single solar cell. Incident radiation 2.45 GHz. Horizontal 2 mm sec/div; vertical 0.02 V/div. (a) Top contact fingers parallel to E-field. (b) Top contact fingers perpendicular to E-field.

the E-field is perpendicular to the fingers. It is expected that this effect will be frequency dependent.

The results in Figures 11 and 12 show approximate values for the voltages induced in combinations of solar cells. There were problems that developed with these measurements that, because of time limitations, were not fully resolved. There were instances when the voltage would increase with increasing time of exposure. Other times the voltage would decrease with increasing time of exposure. There were even cases when the polarity of the voltage changed. Most of these conditions were traced to problems with poor solder connections. However, not all of the unusual voltages were eliminated, and the causes for these effects may be worthy of further study.

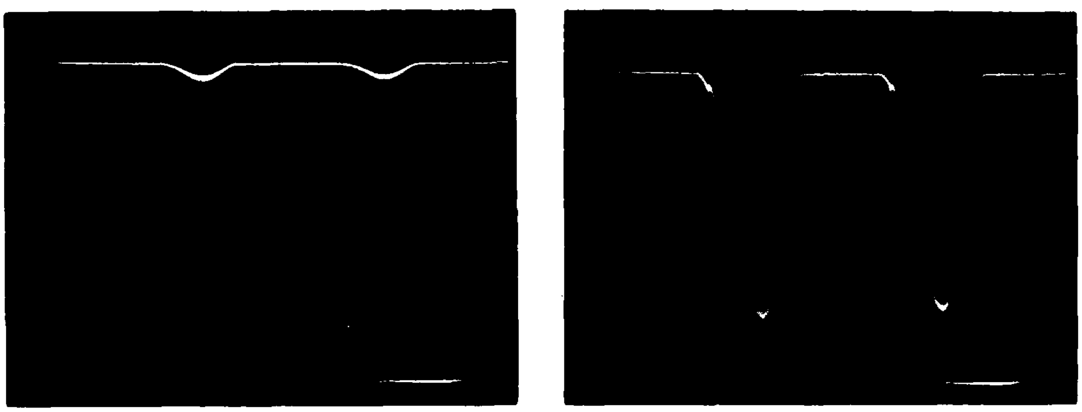
MICROWAVE HEATING OF SOLAR CELLS

The heating of the solar cells that was noted during the experiments prompted a limited investigation of the heating of the cells by microwaves. Based on the knowledge that the voltages induced in the cell were rather low, it was assumed that the heating was primarily dielectric heating. Also, since the dielectric loss factor for glass is usually rather low, it was assumed that the dielectric heating was primarily in the silicon. From this it was estimated (see Appendix II) that the time rate of change of temperature of silicon would be approximately



(a) (b)

Fig. 11. Voltage across 4 solar cells in series.



(a) (b)

Fig. 12. Voltage across 4 solar cells in parallel.

$$\frac{dT}{dt} \cong 5.67\ (10^{-6})\ E^2 \qquad \frac{°C}{sec} \tag{8}$$

This would imply that, in the waveguide when the E field is approximately 15,000 volts per meter, the temperature would increase at the rate of 1275° C per second. However, this calculation does not take into account the fact that the signal level is reduced by a factor of 0.0023, as was noted earlier. This would reduce the temperature change to approximately 0.00675°C per second or about 0.4°C per minute. None of these calculations account for cooling effects that would take place, because it could be assumed that, in space, the only form of cooling would be by radiation and that, over the time involved, this type of cooling would be negligible.

Attempts were made to obtain measurements of the temperature changes that were produced by microwave heating of solar cells. Since direct measurements using thermocouples cannot be made while the cell is being irradiated, attempts were made to measure the temperature immediately after the microwave power was shut off. This did not prove to be very satisfactory because of problems with thermocouple size, affixing the thermocouples to the solar cell, and the like.

The next approach to this problem was to investigate the use of an infrared "gun." Because the gun averaged the temperature over an area two inches in diameter and the solar cells would not cover the entire field of view, this approach to making temperature measurements was not used.

Preliminary measurements were made using an infrared camera (AGA Thermovision, Model #661). In these experiments the solar cells were

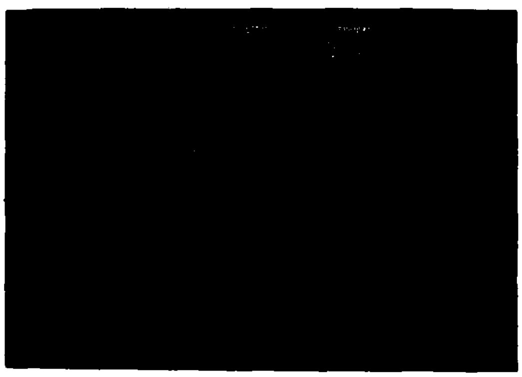
placed 20 centimeters from the horn antenna and radiated with indicated power levels of from 250 watts to one kilowatt. Pictures were taken of the display from the infrared system both before and after microwave heating. Examples of the set-up and type of response indicated by the infrared camera are shown in Figures 13 and 14 respectively. A good deal of work would be required before quantitative values could be obtained for the temperature changes that were produced.

Additional study is needed because the cover glass cuts off some of the infrared from the silicon, the actual temperature values have to be determined from the color of the display and camera sensitivity settings, and the temperature changes were so rapid it was not possible to "capture them" with a still camera. An approach to the latter problem would be to take motion pictures of the display and obtain temperature measurements by "reading" each frame of the film. Additionally, it would be necessary to determine actual E-field values at the solar cell position. This subject could be studied in more detail.

DISCUSSION

It may be concluded that microwave energy from radar and communications sources would have little if any effect on solar cells or solar cell systems. The situations where microwaves could induce voltages in a solar cell or a solar cell system would require extremely high signal levels ($\gtrsim$ 10,000 V/m), and the resulting voltages would still only be in the millivolt range. It was established that high levels

Fig. 13. Laboratory set-up for monitoring the temperature of solar cells heated by microwaves. Infrared camera at upper left, horn antenna and solar cells in the center, and microwave source at right.



(a)

(b)

Fig. 14. Example of infrared display of heating of solar cells by microwaves. (a) Ambient. (b) Heating for 20 seconds.

of microwave power could short out solar cells and cause arcing from different parts of solar cell systems. This aspect of the effect of microwaves on solar cells may be worthy of more study.

In a preliminary investigation of the heating of solar cells by microwaves, the heating rate, when the incident electric field was 15,000 volts per meter, was calculated to be about 0.4°C per second. Since this calculated rate appeared to be much slower than that encountered in practice, additional work should probably be done to determine the heating when solar cells are irradiated by microwaves.

A number of unusual voltages were noted during experiments on combinations of solar cells. While the sources of most of these voltages were located and eliminated, there was one result that could not be explained. That was an apparent reversal of polarity of the diodes in a 4-cell series combination of solar cells. The voltages produced across this configuration reached as high as two volts, which was much higher than was expected. However, with increased exposure to microwaves the signal level would decay to zero and then change to the polarity expected under normal circumstances. While this effect could be eliminated, the reasons for its occurrence could not be explained. Unfortunately there was not enough time to look into this subject, but the unknowns that exist should be resolved.

ACKNOWLEDGMENTS

This work was supported by the Air Force Office of Scientific Research and the Engineering Research Institute of Iowa State University. The author gratefully acknowledges this support.

APPENDIX I

Input Impedance at 2.45 GHz

At palladium silver interface

$$\eta_6 \text{ for silver} = 0.0125 + j0.0125$$

$$\text{Therefore } \eta_{5-6} = 0.0125 + j0.0125 \; \frac{377 + (0.0125 + j0.0125) \tanh \gamma d}{0.0125 + j0.0125 + 377 \tanh \gamma d}$$

$$\gamma \text{ for silver} \cong (7.725)(10^5)(1 + j1)$$

$$\text{Therefore } \gamma d = 2.316 \; (1 + j1)$$

$$\eta_{5-6} \cong 0.0125 + j0.0125$$

When this impedance is transferred back successively through the palladium, titanium, and aluminum, the result is that the input impedance at the silicon-aluminum interface is still approximately 0.0125 + j0.0125. (This result agrees with work by Peralta* that says that the film, which is thinner than a skin depth, must be effectively "in parallel" with the intrinsic impedance of the region in back of the conductor.)

The impedance at the glass-silicon interface becomes

$$\eta_{silicon} \cong 3.3 + j28.3$$

$$\gamma_{silicon} \cong 286.6 + j337.2$$

$$\gamma d \cong 0.08 + j0.0944$$

$$\eta = 33.3 + j28.3 \; \frac{(0.0125 + j0.0125) + (33.3 + j28.3) \tanh \gamma d}{(33.3 + j28.3) + (0.0125 + j0.0125) \tanh \gamma d}$$

$$\cong j5.39$$

*Peralta, E. J., "Electromagnetic Backscattering of Thin Conductive Films," IEEE Transactions on Antennas and Propagation AP-19-1, January 1971.

η_1 for the glass $\cong$ 193

β_1 for the glass $\cong$ 51.3

β_d for the glass $\cong$ 0.0118

$$\eta_{0-1} = 193 \; \frac{j5.39 + j193 \tan \beta d}{193 + j\;(j5.39) \tan \beta d}$$

$$\eta_{0-1} \cong j7.66$$

$$\text{Thus } \Gamma = \frac{\eta_{0-1} - 377}{\eta_{0-1} + 377} \cong -0.9992 + j0.041$$

$$\cong \; 177.7°$$

at 100MHz $\quad \eta_{0-1} \cong 0.15$

$\quad |\Gamma| \cong 1.0$

at 10 GHz $\quad \eta_{01} \cong j40.82$

$\quad |\Gamma| \cong 1$

at 100 GHz $\quad \eta_{01} \cong 5.93 + j2.65$

$\quad |\Gamma| \cong 1$

Thus, the solar cell acts like a low impendance load to microwaves from 100 MHz to 100 GHz, and microwaves would tend to be reflected from the solar cells.

APPENDIX II

Microwave Heating of Solar Cells

The heating of a material exposed to electromagnetic energy may be approximated by knowing that the power absorbed as a result of dielectric losses is given by the equation

$$P = 55.63 \times 10^{-12}\ fE^2\varepsilon_r'' \qquad \mathrm{W/m^3} \qquad (1)$$

where f is the frequency in Hertz, E is the rms local field intensity in volts/meter, and ε_r'' is the relative dielectric loss factor (dimensionless). When P is the power absorbed, given by Equation (1), the local heating rate will be

$$\frac{dT}{dt} = \frac{0.239 \times 10^{-6}}{C\rho}\ P \qquad {}^\circ\mathrm{C/sec} \qquad (2)$$

where C is the specific heat in cal/g°C, and ρ is density in g/cm^3. For silicon C = 0.181 cal/g°C, ρ = 2.328 g/cm^3, and ε_r'' = 73.41. Thus the time rate of change of temperature for silicon at 2.45 GHz is

$$\frac{dT}{dt} = 5.67\ (10^{-6})\ E^2 \qquad {}^\circ\mathrm{C/sec} \qquad (3)$$